Electron Beam Transport and its Symmetric Energy Distribution

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Abstract – In thee explosive electron emission with low energy high current system, the electron beam transport in the long space with its symmetric energy distribution against the work centerline is an inevitable task to homogeneous surface treatment and its modification. In case the energy is not distributed symmetrically, the work is irradiated with electron beam non-homogeneous and much of the cracks and craters were generated. The beam transport was analyzed with algorism calculation and the optimized condition to distribute the energy symmetrically was determined through the systems modification. Here we present the outline of the calculation and its effect to transport the long space. Then the system modification including the magnetic field changes were presented to acquire the symmetric energy distribution with some case histories of the commercialized application. The application histories refer with metallic substrates and organic plastic lenses also.

1. Introduction

Electron beams with high density of energy find the application in various technological processes connected with change of the condition and properties of materials surface. A wide application have received low energy (up to 30 keV) electron sources with plasma filled the diode and the explosive-emission cathode [1]. The system with low energy electron beam of the large area has been developed in Nagata Seiki Co.,Ltd. (Japan) in cooperation with HCEI (Russia). A series of such machines is released. Low energy electron beam the big area with the maximal diameter 60mm is used for fusion and evaporation of a surface of metal, for modification the surface of plastic lenses, modification of stomatological materials [2, 3]. The irradiation is carried out by an electron beam in series of pulses at scanning the product under beam. While in service setups electron beam processing of materials surface have been revealed number of lacks negatively influencing on out put parameters of the setup. First of all, unstable distribution of energy on beam section, parameters spread from setup to setup. Unstable work of electron gun at the big distances from a edge gun to a collector. In this connection there is a problem of good reproducibility of beam with the set parameters, uniformity of a stream electron in cross-section of beam. Lack of sources with the explosive-emissive cathode, non-uniform distribution of energy on section of beam and unstable position of beam concerning an axis of gun. It is connected to statistical point character of explosive emission from the cathode. Besides for high-current electron beams it is not enough to receive homogeneous emission from the cathode. As process of formation and transport of a electron beam is carried out in strong electric and a magnetic field of beam, distribution of density of current and energy can change essentially by interaction with an external leading magnetic field. The decision of these questions stimulated theoretical and experimental investigations of influence of external magnetic field on formation and transportation of electron beam.

2. Experimental setup

The scheme of experimental setup is shown in Fig. 1.

The electron gun with the explosive emission cathode and the plasma anode was used. The plasma anode was formed in high-current Penning discharge.

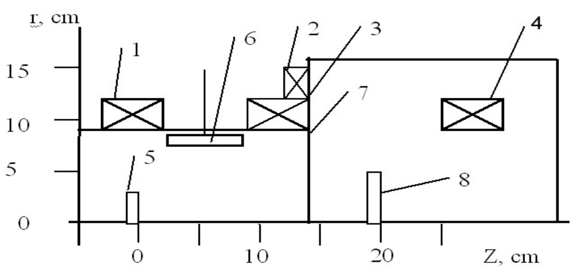


Fig. 1. Scheme of electron gun. 1 – upper coil; 2 – control coil; 3 – lower coil; 4 – additional coil; 5 – cathode; 6 – anode; 7 – drift pipe edge (chamber); 8 – collector

Cathodes penning discharge – a collector with samples and the cathode of a gun earthed. The cathode of a gun earthed through the diode and the resistor. Diameter of the cathode is 6 cm. The anode (6) the thin cylinder in diameter 100 mm and long 20...100 millimeters. Working gas is argon having the pressure 0.05 Pa.

At the first stage an accelerating gap and space of drift it was filled by plasma with concentration of 10^{11}–10^{13} cm^{-3}. The plasma column was formed at volumetric ionization of gas at the high-current stages of the Penning discharger.

Then on the gun cathode (5) the accelerating pulse voltage was applied. Under action of strong electric field on the cathode dense metal plasma is formed. The stream electrons accelerated in double layer between cathode and anode plasma is transported in the plasma channel to a collector with samples (8). The leading magnetic field is formed by magnetic coils (1, 3, 4). The basic magnetic coils had on 270 turn everyone. The control magnetic coil (2) was used for focusing and transformation of a beam. The control coil settled down atop of the basic coil and had 135 turns. In experiments on beam compression magnetic coils (1, 2, 3) were used. Coils (2, 3) were included according to (1) as subtractive polarity. The magnetic field in working zone of setup was created by magnetic coils of a gun (1, 3) and the additional coil (4). The field created by magnetic system can be changed from 0.5 kG up to 5 kG. Let's note that the magnetic system of the serial machine will consist of two coils (1, 3). Energy of electron beam was measured by calorimeter with a working diameter 80 mm. Diameter of beam on target was supervised on print on samples from stainless steel. Energy distribution on section of beam was supervised with the help of a calorimeter with nine sensor controls. Diameter of separate sensor is 5 mm. Results averaged on 20 shots. Calorimeter established on a place of a sample. An accelerating voltage was 25 ... 30 kV.

3. Theoretical results

The investigation of transporting and the focusing of low-energy electron beams in plasma at fill charge neutralization in external and self-field was carried. The equation set was solved in Cartesian coordinate system with z axis oriented in beam movement direction along drift tube axis. The current neutralization degree was determined numerically according with model [4], tacking into account ionization of argon by electron beams at pressure p=0.01–0.05 Pa. Presented equation set with model [5] permit to investigate the movement of beams electrons and to construct the beams envelop in non uniform fields tacking into consideration of changes its radius $r_b(z)$, of current density and of current neutralization degree. In general formulation tacking into account changes of beam parameters and different relations of external and self-magnetic fields the equation set was solved numerically.

The nonuniform magnetic field is described by function $B_z=B_{z0}\exp[-(z_m-z)^2/1.44a^2]$, where a – parameter defines the fields gradient $B_z(z)$, at $z=z_m-a$ the field is a half in comparison with maximal value B_{z0}. Such dependence corresponds to field on solenoid input at $z<z_m(B_r>0)$ and on solenoid output at $z>z_m(B_r<0)$ in real experimental machine shown on the Fig. 1.

The results of analytical investigation of transporting of charge-neutralized beam in non uniform magnetic fields show that in such conditions electrons movement consist in two rotation which represent the hybrids of frequencies:

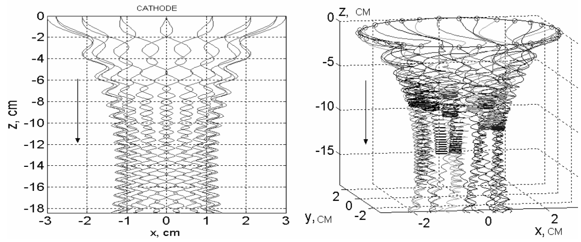
$$\Omega_0 = eB_z/\gamma m_0 c, \quad \Omega_r = \sqrt{e\,|\,B_r\,|\,\beta_z/\gamma m_0},$$
$$\Omega = \{(2c^2/r_b^2\beta_z\gamma)\,(I_b/I_{A0})\,A\}^{1/2},$$

and in compare with relation of components B_r, B_φ, B_z it can be changed in the broad limits. At domination of field B_z (Ω_0>>Ω, Ω_r), the electrons rotation have a place with a high frequency $\approx\Omega_0$ and small radius of rotation around driving center and slow rotation around beams axis with radius $r_b(z)$. The beams envelop depends on B_{z0}, fields gradient $B_z(z)$, current density, electrons energy and current neutralization degree. At the same time in contrast to case of uniform magnetic field here is area of parameters where beam can be confinement by using of definite fields $B_z(z)$.

In other to obtain the needed beams parameters on target the investigations of beams transporting at different configuration of fields in drift space were carry out. The configuration of fields in drift space which ensure the beams focusing on target tacking into account plasma density creating by beam and different current neutralization.

The numerical experiments were realized at different beam current values. The beam current density determined by accelerating voltage was retained constant. Beam compression shown on the Fig. 2 corresponds to beam parameters on cathode: beam radius r_{b0}=3 cm, current I_b=15 kA, current neutralization f_M=0.5, B_{z0}=3 kG. The beam focusing takes a place at the definite configurations of external magnetic field. The beams compression to 1 cm in target area is possible for beam parameters aforesaid (Fig. 2, *a*). At further increasing of field gradient in drift space take place the pinch effect of beam. The beam is reflected and can not come up to target. The pinch effect connected with transverse electrons velocities which its obtains in self magnetic field. With increasing of current neutralization of beam the transverse electrons velocities slow down and beam come to the target completely.

Results of numerical modeling of beam focusing with electron spread at velocity tg$\theta=v_\perp/v_z$=0.26 (θ~16°) in non uniform field are shown on Fig. 2, *b*. As can be seen from Fig. 2, *b* in the presence of electron spread at velocity beam focusing is retained, but part of electrons at big $v_\perp/v_z$ and high beam current can not come to the target because of high initial transverse velocity. At decreasing of electron scattering ~10 % and decreasing of current on input in drift space – 1–3 kA this losses disappears practically.



(a) (b)

Fig. 2. Configurations of electron beam

On the Fig. 3 it is shown the dependence of pinch effect coordinate from the current neutralization degree. Curves 1 and 2 correspond to different magnetic field gradient levels ($a_1 > a_2$). The coordinate of drift tube edge is $z = -14$ cm.

On the Fig. 4 it is shown the dependence of beam radius on target from magnetic field on drift tube edge, at different initial beam radii on the cathode: curve 3–r_{b0}=3 cm, 2 – 2 cm, 1 – 1 cm. At that the current density is not change: j_b=0.53 kA/cm^2.

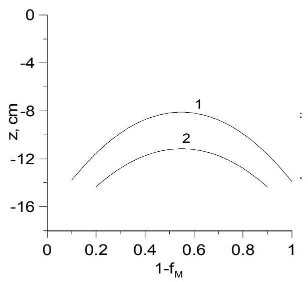


Fig. 3. Pinch effects coordinate

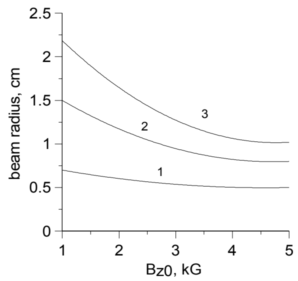


Fig. 4. Beam radius from a magnetic field

For realization of needed magnetic field configuration the coils configurations and its position were selected with the help of PIC method and ANSYS software. The additional investigation of electron beam transporting in plasma was carry out with using of PIC method. The good agreement of results with beam envelop method [5] was obtain.

4. Experimental results and discussions

Homogeneous enough print in diameter 50 mm has been received in quasi-homogeneous a magnetic field 2.5 kG created by two coils (1, 3). However at processing some materials (plastic lenses) and products with the big area when it is necessary to scan a product under a beam, significant heterogeneity of print on surface of the product has been found out. The analysis has shown that heterogeneity is connected to a wide spacing energy in a pulse from shot to shot and with non-uniform energy distribution on beam cross-section.

Distributions of energy density on beam section in a series from 20 shots are shown in Fig. 5. A bold line it is average value of energy in beam. The analysis of prints and the received distributions has shown that the size of prints approximately corresponds to a flat part of average density of energy 6 J/cm^2.

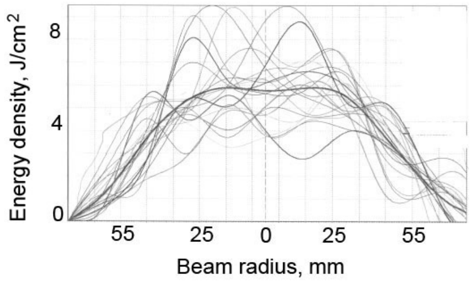


Fig. 5. Radial distributions of a beam energy

In a non-uniform external magnetic field it is possible to stabilize position of a maximum of a beam on a target and if necessary to carry out compression of a beam. Fig. 6 presents distribution of intensity of an external magnetic field along an axis of a gun. For amplification of focusing action of a magnetic field on a beam it is offered to use the additional focusing coil (the control coil) (2) (Fig. 1). With the help of three coils it is possible to create an external magnetic field of a various configuration. Experiments have shown that on focusing of a beam the basic influence renders a gradient of a magnetic field along an axis of a gun. Results of experiment will well be coordinated to results of calculations of focusing of an electron beam at a stage of transportation the electrons to target.

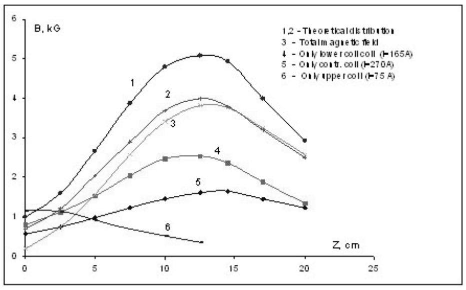


Fig. 6. Magnetic field distribution on a gun axis

Changing gradient of field, at the expense of change of configuration of magnetic field it is possible to operate the beam size in a pipe of drift and behind its limits.

With increase in the field gradient on an axis, at the expense of increase in field intensity in the bottom part of a gun and increase in the counter field at the cathode, beam diameter decreases more than in 2 times magnitude in comparison with diameter of the cathode. Position maximum energy of the beam concerning an axis of a gun, (Fig. 7) is more rigidly stabilized. Disorder on energy no more than 25 %. The density of energy in a beam thus is reduced on 20...30 % and makes 4,5...6 J/cm^2. These results will well be coordinated to theoretical calculations.

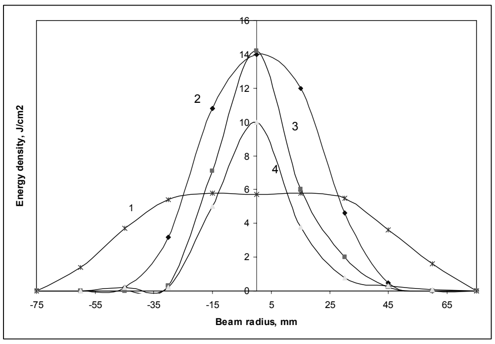


Fig. 7. Cross-sectional beam energy density distribution for different the magnetic field gradient. 1 – uniform field; 2 – 180 G/cm; 3 – 300 G/cm; 4 – 350 G/cm

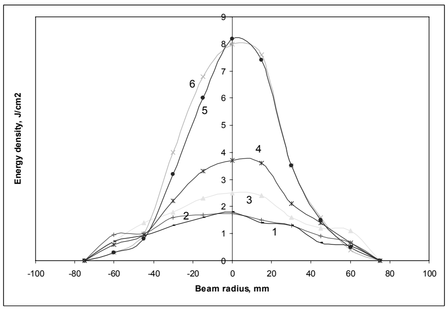


Fig. 8. Radial distributions of a beam energy on distance 1, 2 – 140 mm; 3–6 – 100 mm; 1, 4, 6 – 300 G/cm; 2, 3, 5 – 190 G/cm

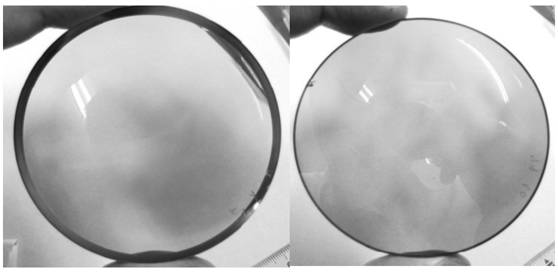


Fig. 9. Electron beam irradiated plastic lens 5 J/cm^2, 30 kV

In Fig. 8 curve distributions of density of energy on beam section for distance from a cut of a gun up to collector 140 mm curves 1, 2 and 100 mm curves 3–6 are submitted. The non-uniform magnetic field was created or inclusion of one coil (2), curves 2, 3, 5 or counter inclusion of coils (1, 3) – curves 1, 4, 6. On these distances at any inclusion of coils (1–3) energy of a beam did not exceed – 1...3 J/cm^2. Such significant decrease of energy of the electron beam is connected by that transportation electrons is carried out in missing magnetic field and in plasma with low concentration of particles. Theoretical calculations have shown, that for transportation of an electron beam with power efficiency about 40 % it is necessary to create the plasma channel with density of plasma more $9\cdot10^{11}$ cm^{-3}. In this case there is a full charging neutralization and high enough current neutralization of a beam. Transportation electron beam to a target with higher power efficiency can be carried out in a homogeneous magnetic field. Quasi-homogeneous the magnetic field in a working zone of setup was created by the additional magnetic coil (4) Fig. 1. The additional coil was included according to with the coil (3). As follows from Fig. 8, creation quasi-homogeneous a magnetic field 2...3,5 kG in a working zone of setup has allowed to increase in 2–3 times energy of the beam by targets, curve 5, 6. Thus, the magnetic system consisting of three magnetic coils (1, 2, 4) allows to generate in the channel of drift of the gun an electron beam with the necessary parameters and effectively to carry out its transportation target.

Fig. 9 plastic lenses which surface is modified by an electronic beam are shown. The lens (a) was irradiated with a beam distribution of energy density close to distribution shown on Fig. 5, a lens (b) the beam with distribution (2) (Fig. 7). It is visible, that stabilization of position of the beam in space allows to carry out more homogeneous updating of the surface of a material.

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